

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)

17-05-2004

REPRINT

4. TITLE AND SUBTITLE

Long-term Trends in Interplanetary Magnetic Field Strength
And Solar Wind Structure During the Twentieth Century

5a. CONTRACT NUMBER**5b. GRANT NUMBER****5c. PROGRAM ELEMENT NUMBER**

61102F

5d. PROJECT NUMBER

2311

5e. TASK NUMBER

RD

5f. WORK UNIT NUMBER

A1

6. AUTHOR(S)

I.G. Richardson*, E.W. Cliver and H.V. Cane**

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/VSXBS
29 Randolph Road
Hanscom AFB MA 01731-3010

8. PERFORMING ORGANIZATION REPORT

20040526 030

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFRL/VSXBS**11. SPONSOR/MONITOR'S REPORT
NUMBER(S)**

AFRL-VS-HA-TR-2004-1093

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited.

*NASA Goddard Space Flight Center, Greenbelt, MA; **NASA Goddard Space Flight Center,
Greenbelt, MD

13. SUPPLEMENTARY NOTES

REPRINTED FROM: JOURNAL OF GEOPHYSICAL RESEARCH, Vol 107, No. A10, 1304,
doi: 10.1029/2001JA000507, 2002

14. ABSTRACT

Lockwood et al (1999) have recently reported a ~40% increase in the radial component of the interplanetary magnetic field (IMF) at Earth between 1964 and 1996. We argue that this increase does not constitute a secular trend but is largely the consequence of lower than average fields during solar cycle 20 (1964-1976) in comparison with surrounding cycles. For times after 1976 the average IMF strength has actually decreased slightly. Examination of the cosmic ray intensity, an indirect measure of the IMF strength over the last five solar cycles (19-23) also indicates that cycle averages of the IMF strength have been relatively constant since ~1954. We also consider the origin of the well-documented increase in the geomagnetic aa index that occurred primarily during the first half of the twentieth century. We surmise that the coronal mass ejection (CME) rate for recent solar cycles was approximately twice as high as that for solar cycles 100 years ago.

15. SUBJECT TERMS

Solar variability
Solar wind

Cosmic rays

Interplanetary magnetic fields

16. SECURITY CLASSIFICATION OF:

a. REPORT
UNCLAS

UNCLAS

c. THIS PAGE
UNCLAS

**17. LIMITATION
OF ABSTRACT**

SAR

**18. NUMBER
OF PAGES**

7

19a. NAME OF RESPONSIBLE PERSON

E. W. Cliver

**19b. TELEPHONE NUMBER (include area
code)**

781-377-3975

Long-term trends in interplanetary magnetic field strength and solar wind structure during the twentieth century

I. G. Richardson¹

NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

E. W. Cliver

Air Force Research Laboratory, Hanscom Air Force Base, Bedford, Massachusetts, USA

H. V. Cane²

NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Received 28 September 2001; revised 20 November 2001; accepted 21 November 2001; published 17 October 2002.

[1] *Lockwood et al.* [1999] have recently reported a $\sim 40\%$ increase in the radial component of the interplanetary magnetic field (IMF) at Earth between 1964 and 1996. We argue that this increase does not constitute a secular trend but is largely the consequence of lower than average fields during solar cycle 20 (1964–1976) in comparison with surrounding cycles. For times after 1976 the average IMF strength has actually decreased slightly. Examination of the cosmic ray intensity, an indirect measure of the IMF strength, over the last five solar cycles (19–23) also indicates that cycle averages of the IMF strength have been relatively constant since ~ 1954 . We also consider the origin of the well-documented increase in the geomagnetic *aa* index that occurred primarily during the first half of the twentieth century. We surmise that the coronal mass ejection (CME) rate for recent solar cycles was approximately twice as high as that for solar cycles 100 years ago. However, this change in the CME rate and the accompanying increase in 27-day recurrent storm activity reported by others are unable to account completely for the increase in *aa*. Rather, the CMEs and recurrent high-speed streams at the beginning of the twentieth century must have been embedded in a background of slow solar wind that was less geoeffective (having, for example, lower IMF strength and/or flow speed) than its modern counterpart. **INDEX TERMS:** 1650 Global Change: Solar variability; 2104 Interplanetary Physics: Cosmic rays; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536); 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; **KEYWORDS:** interplanetary magnetic field, geomagnetic activity, cosmic rays, solar wind, long-term trends

Citation: Richardson, I. G., E. W. Cliver, and H. V. Cane, Long-term trends in interplanetary magnetic field strength and solar wind structure during the twentieth century, *J. Geophys. Res.*, 107(A10), 1304, doi:10.1029/2001JA000507, 2002.

1. Introduction

[2] Recently, *Lockwood et al.* [1999] [see also *Stamper et al.*, 1999; *Lockwood and Foster*, 2000; *Lockwood*, 2001] reported a $\sim 40\%$ increase in the radial component of the interplanetary magnetic field (IMF) since the beginning of in-situ observations by spacecraft in the early 1960s. Moreover, they used the geomagnetic *aa* index [*Mayaud*, 1972] and solar wind data to infer that a doubling of the solar open magnetic flux has taken place since ~ 1900 . Here, we first examine IMF and galactic cosmic ray (GCR) data to deter-

mine in what sense, if any, the reported $\sim 40\%$ IMF increase from 1964–1996 constitutes a trend. The cosmic ray data are relevant to this question because, as has been noted by several authors [e.g., *Slavin and Smith*, 1983; *Cane et al.*, 1999a, 1999b; *Belov*, 2000], the GCR intensity tends to anticorrelate with the IMF strength. If there were a long-term increase in the IMF, then we might also expect a general decline in the GCR intensity with time. Such a decline has been reported by *Stamper et al.* [1999] for the 1964–1996 interval. In this paper, we suggest that these reported changes in the IMF and GCR intensity in 1964–1996 are not indicative of true long-term trends. In particular, IMF observations since 1976 actually suggest a decline in the average field strength.

[3] As the second aspect of this study, we examine the cause of the remarkable rise in the geomagnetic *aa* index during the twentieth century, as noted by *Lockwood et al.* [1999] and others [e.g., *Russell*, 1975; *Feynman and*

¹Also at Department of Astronomy, University of Maryland, College Park, Maryland, USA.

²Also at School of Mathematics and Physics, University of Tasmania, Hobart, Australia.

Crooker, 1978]. The principal increase in aa was completed by ~ 1950 and average activity levels since then have remained relatively constant. The increase was so pronounced that the lowest activity levels observed after 1950 tend to be higher than the maximum levels observed early in the century. Since the long-term variability in aa closely reflects the envelope of sunspot maxima [e.g., Cliver *et al.*, 1998] and the rate of coronal mass ejections (CMEs) tracks the sunspot number, at least in recent cycles [Webb and Howard, 1994; Cliver *et al.*, 1994], one possible cause of the secular increase in aa from $\sim 1900 - 1950$ is a change in solar wind structure over this period, with CMEs, which generate the vast majority of large geomagnetic storms [Gosling *et al.*, 1991; Richardson *et al.*, 2001], occurring with increasing frequency. But was this the sole cause of the long-term increase in aa , or was there an increase in the geoeffectiveness of all components of the solar wind (i.e., slow solar wind, high-speed streams and CME-related structures)? We will address these questions by apportioning geomagnetic activity at the beginning of the twentieth century to the various solar wind flow types based on an analysis for recent cycles [Richardson *et al.*, 2000, 2002], and also by comparing geomagnetic activity for the aa minimum years of 1901 and 1977.

2. IMF Variation During the Space Age

2.1. Is There a Long-Term Trend in In Situ Observations of the IMF?

[4] We first consider the report by Lockwood *et al.* [1999] and Stamper *et al.* [1999] that the radial component of the near-Earth IMF has increased in strength by $\sim 40\%$ since in-situ observations began in 1963. Figure 1b shows Carrington-rotation averages of the magnitude of the radial component of the IMF ($|B_r|$) from the NSSDC OMNI data base. The solid line through these data shows the linear fit to annual IMF averages for 1964–1996 obtained by Stamper *et al.* [1999] (from their Table 2). Over this interval, the fit clearly indicates an increase in $|B_r|$. We are reluctant, however, to interpret this increase in terms of a long-term trend in the IMF. Figure 1a shows Carrington-rotation averages of the solar 10 cm flux, an indicator of solar activity levels, for the three cycles (20–22) considered by Lockwood *et al.* and Stamper *et al.* together with the decline of cycle 18, cycle 19, and the rise of the current cycle (23). The radial component of the IMF clearly shows variations associated with the solar activity cycle which are most prominent in cycles 21 and 22. When the radio and IMF data are considered together, it appears that the rising IMF “trend” from 1964–1996 is primarily due to low field values measured during weak cycle 20, followed in cycles 21 and 22 by a return to the higher IMF values inferred for cycle 19 from the intense 10 cm emission during that cycle. If fits are made to other intervals, then quite different trends are obtained. For example, the dotted line with a solid circle at each end in Figure 1b shows that the fit for 1976–1996 (i.e., omitting the first cycle of the Stamper *et al.* interval) has no overall trend. The fields observed from 1996 to 2000 in cycle 23 appear to fall below the trend line obtained by Stamper *et al.* [1999] (though we note that the pattern in previous cycles (Figure 1) suggests that stronger fields might occur following the maximum of this cycle). In fact,

a linear fit to data from 1976–present (the dashed line in Figure 1b) indicates a decline in the average IMF strength during this period. Finally, a fit to the complete period of $|B_r|$ data in Figure 1 (not included in the figure) shows an increase from ~ 3.03 nT to ~ 3.53 nT. This increase of $\sim 17\%$ is much smaller than the $\sim 40\%$ reported by Stamper *et al.* [1999] for a subset of these data. Again it should not be interpreted as a “long-term” trend because it is sensitive to the endpoints of the relatively short period of data fitted.

[5] The increase in the aa index (also $\sim 40\%$) from 1964–1996 reported by Stamper *et al.* [1999] is similarly sensitive to the interval considered. The aa index is shown in Figure 1c. As was the case for $|B_r|$, the putative trend during the space age (solid line) appears to result from the weaker than (recent) average cycle 20. A fit to data for 1954–1996 (dashed line) indicates a much weaker upward trend of 0.09 ± 0.02 nT/year, while that for the complete interval shown in Figure 1 (not included in the figure) shows no significant trend (0.02 ± 0.02 nT/year).

2.2. IMF Strength Since 1951: Implications From Galactic Cosmic Ray Observations

[6] Another way of inferring whether there has been a change in the IMF intensity at Earth during recent solar cycles is to consider changes in the cosmic ray intensity. Figure 1d shows solar-rotation averages of the cosmic ray intensity measured by the University of Chicago Climax neutron monitor (cut-off rigidity ~ 3 GV) since the beginning of observations in 1951. Note that the cosmic ray intensity is anti-correlated with solar activity levels, and that the size of the depression at solar maximum is roughly correlated with the size of the solar cycle and with the associated magnetic field increase, as has been previously reported [e.g., Slavin and Smith, 1983; Cane *et al.*, 1999a, 1999b; Belov, 2000]. Stamper *et al.* [1999] noted a downward trend in the Climax counting rate from 1964 to 1996 which they interpreted as evidence supporting a long-term trend in the IMF intensity. The solid line in Figure 1d fitting the data for this period has a downward slope of $\sim 0.15 \pm 0.03\%/year$. This behavior results from the weak cosmic ray depression in cycle 20 followed by stronger depressions in the two subsequent solar cycles. Thus, as was the case for $|B_r|$ and aa , we do not take the downward slope in the cosmic ray intensity during this three-cycle period as evidence for a long-term trend. If we consider instead the period from 1954 to 1996 (the minima preceding cycles 19 and 23 respectively), the dashed line indicates that there is a negligible downward trend ($-0.009 \pm 0.02\%/year$). Because of the large amplitude of the solar cycle modulations compared to any long-term change over this interval, we note that the calculated long-term trend is extremely sensitive to the start and end times chosen for the fit.

[7] Another way of examining the cosmic ray data for evidence of long-term trends is to compare the intensities during solar minima. The correct way to do so is to compare intensities in alternate minima where the solar global magnetic field (A) has the same direction. This is because (see Figure 1) the intensity time profiles (peaked or flat when $A < 0$ or > 0 respectively) and maximum intensity attained (at neutron monitor energies, higher when $A < 0$) are influenced by the differences in cosmic ray drift patterns in the heliosphere which depend on A [e.g., Jokipii and

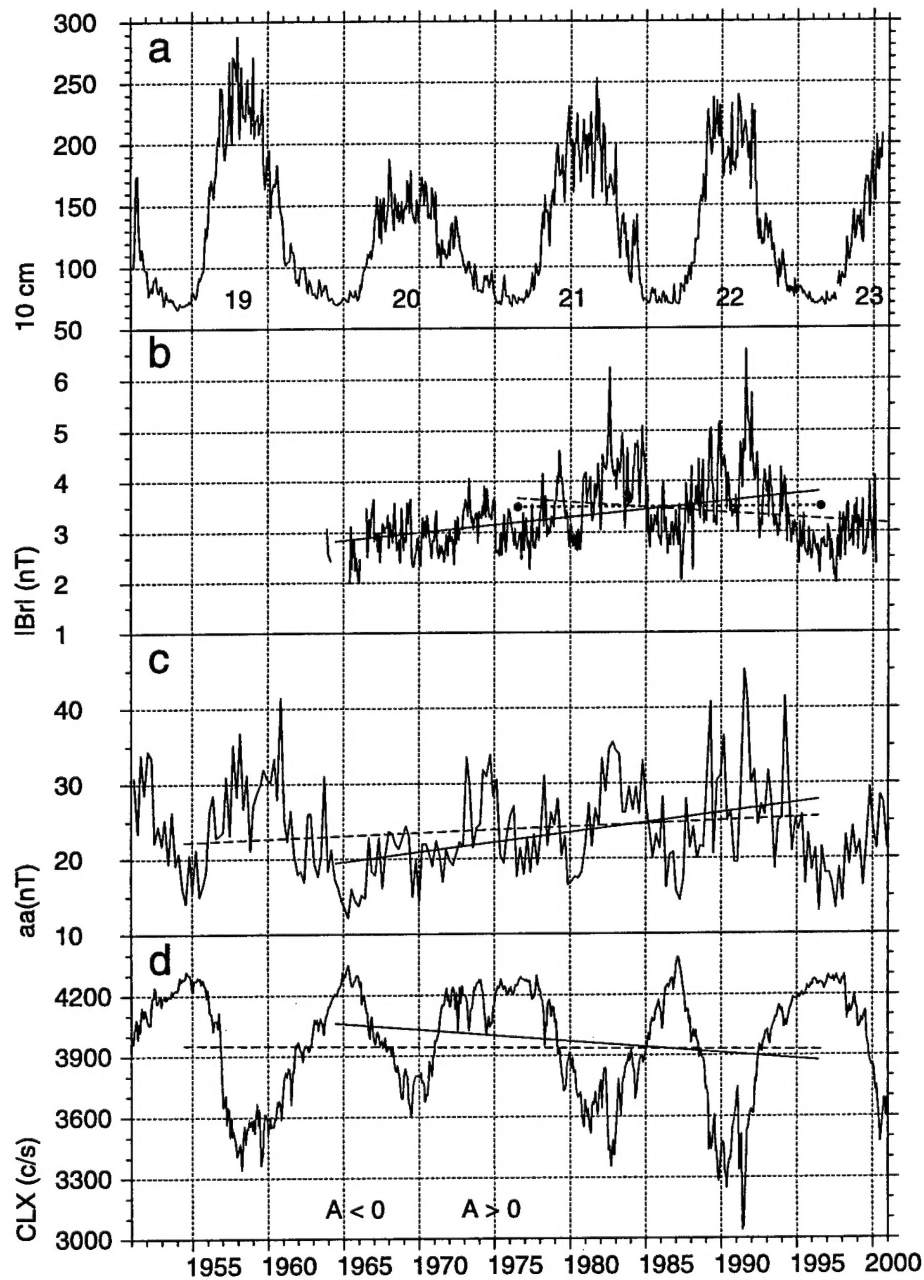


Figure 1. Comparison of (a) the solar 10 cm flux (a measure of solar activity levels), (b) the magnitude of the radial interplanetary magnetic field component near the Earth, (c) the geomagnetic *aa* index and (d) the galactic cosmic ray intensity observed by the Climax neutron monitor from 1951 to 2000. The solid line in (b) indicates the trend in the IMF radial component during 1964–96 inferred by *Stamper et al.* [1999]. A similar fit to data for 1976–1996 (dotted line with circles at each end) shows no trend, while that for 1976–2000 (dashed line) shows a decreasing trend. The solid line in (c) is the trend in *aa* inferred by *Stamper et al.* [1999] for 1964–1996, which is largely the result of weak activity in cycle 20. However, fits to longer intervals indicate much weaker trends (e.g., 1954–1996; dashed line). The cosmic ray data show the anti-correlation between the cosmic ray intensity and solar activity levels and the IMF. A downward trend is inferred from a linear fit to data for 1964–96 (solid line in (d)), as also reported by *Stamper et al.* [1999], but this trend is strongly influenced by the weak cosmic ray modulation in cycle 20. The dashed line, a fit to data from 1954 to 1996 indicates a negligible trend during this longer interval. Likewise, the cosmic ray intensity during (alternate) solar minima (with the same direction of the solar global magnetic field *A*) shows no apparent trend.

Thomas, 1981; Kóta and Jokipii, 1983]. The counting rate of the data in Figure 1 has recovered to approximately the same level (to within < 20 counts/s, i.e. $< 0.5\%$) in minima of the same A epoch since 1954. This is a small fraction ($\sim 3\%$) of the solar cycle modulation, suggesting that if it is attributable to a change in the IMF intensity, this change is small compared to the solar cycle field variation. Thus, the cosmic ray data presented here show little evidence of a significant long-term trend (in particular a decrease) which might be consistent with a long-term change in the IMF strength.

[8] Before leaving this topic, we note that neutron monitor data counting rates may be influenced by factors such as changes in instrumentation (e.g. improvements/malfunctions) requiring careful renormalization, changes in station location, and long-term drifts in geomagnetic cut-offs because of temporal changes in the terrestrial magnetic field, the importance of which will depend on station location [e.g., Popielawska and Simpson, 1991; Shea and Smart, 2000, 2001]. Thus, studies of long-term variations in cosmic ray intensity must ensure that the appropriate corrections have been made. In particular, a drift is known to have occurred in the Climax counting rate relative to other more stable neutron monitors and it is the renormalized data (J. A. Simpson and R. Pyle, "Post-1980 corrections to the Climax, Colorado neutron monitor counting rate", <http://ulysses.uchicago.edu/NeutronMonitor/Misc/neutron2.html>) that are used in Figure 1. Ground level events (rare solar particle events which reach sufficiently high energies to be detectable by neutron monitors) have also been removed from these data. Nevertheless, these corrections are of minor importance to our main point here that the change in cosmic ray intensity inferred by Stamper *et al.* [1999] is the result of fitting to data from the weak cycle 20 and the subsequent two stronger cycles, and does not provide support for their claim of a long-term increase in the IMF during the same period.

3. Increase in the Geomagnetic *aa* Index From ~ 1900 to ~ 1950

3.1. Was the *aa* Increase Due Solely to a Change in Solar Wind Structure?

[9] We now turn to the second main topic of this paper - the cause of the secular increase in *aa* during the first half of the twentieth century. Figure 2b [after Vennerstroem, 2000] shows that, beginning in 1901, cycle-averages of the *aa* index exhibited a remarkable systematic increase during the first half of the twentieth century before settling at a higher level after ~ 1950 . The *aa* index is correlated with $V^2 B_s$, where V is the solar wind speed, and B_s is the southward magnetic field component [e.g., Crooker *et al.*, 1977; Crooker and Gringauz, 1993, and references therein]. Thus, the increase in *aa* during the first half of the twentieth century could be caused by an increase in the average solar wind speed and/or B (assuming an approximately constant proportionality between B and B_s).

[10] Alternatively, it might result from a change in the structure of the solar wind near the ecliptic plane, with, for example, the fraction of the solar wind populated by more geoeffective structures such as shocks and interplanetary coronal mass ejections increasing from $\sim 1901 - 1950$ at the expense of less geoeffective high- and low-speed

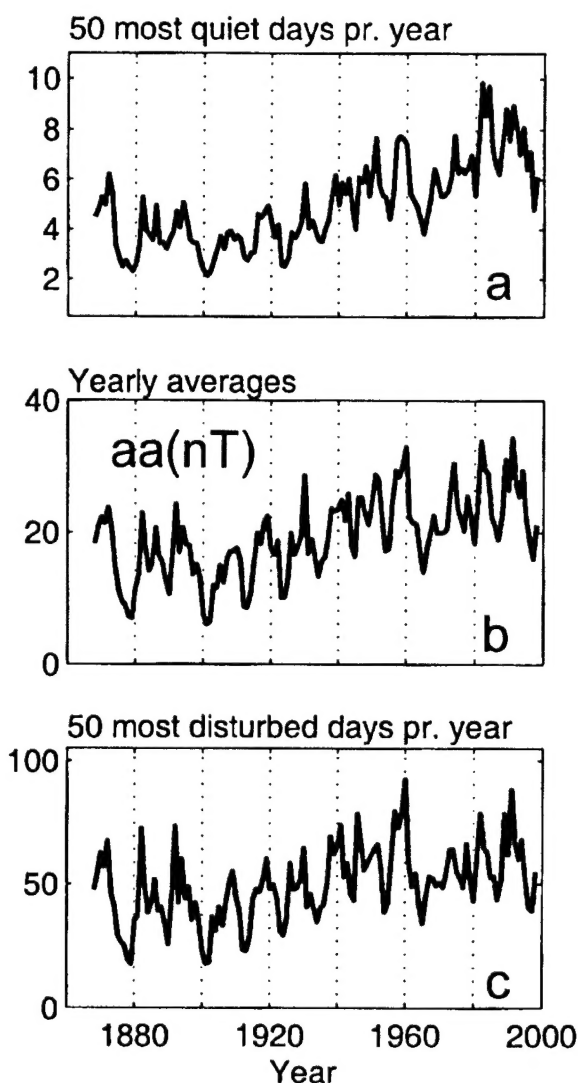


Figure 2. Variation in the yearly averages of *aa* from 1868 to 1999 (b), and for the 50 quietest days (a) and 50 most disturbed days (c) in each year [after Vennerstroem, 2000].

corotating streams. (Other possibilities, such as instrumental or magnetospheric effects, seem to be insufficient to account for this increase in *aa* [e.g., Clilverd *et al.*, 1998].) We will begin by considering whether the secular increase in *aa* resulted entirely from a change in the solar wind structure.

[11] First, we examine whether an increase in the rate of coronal mass ejections could have caused the long-term increase in *aa*. To do this, we use the results of Webb and Howard [1994], who combined coronagraph/photometer data from the Helios 1/2, Skylab, Solwind, and the Solar Maximum Mission spacecraft to obtain daily CME rates from 1974 to 1989, including the maximum of cycle 21. They showed that the CME rate tracked the solar cycle, and produced a correlation plot between yearly averages of the daily CME rate and the sunspot number (SSN). Assuming that this relationship holds for cycles covering a range of peak sunspot numbers, we can use it to infer the daily CME

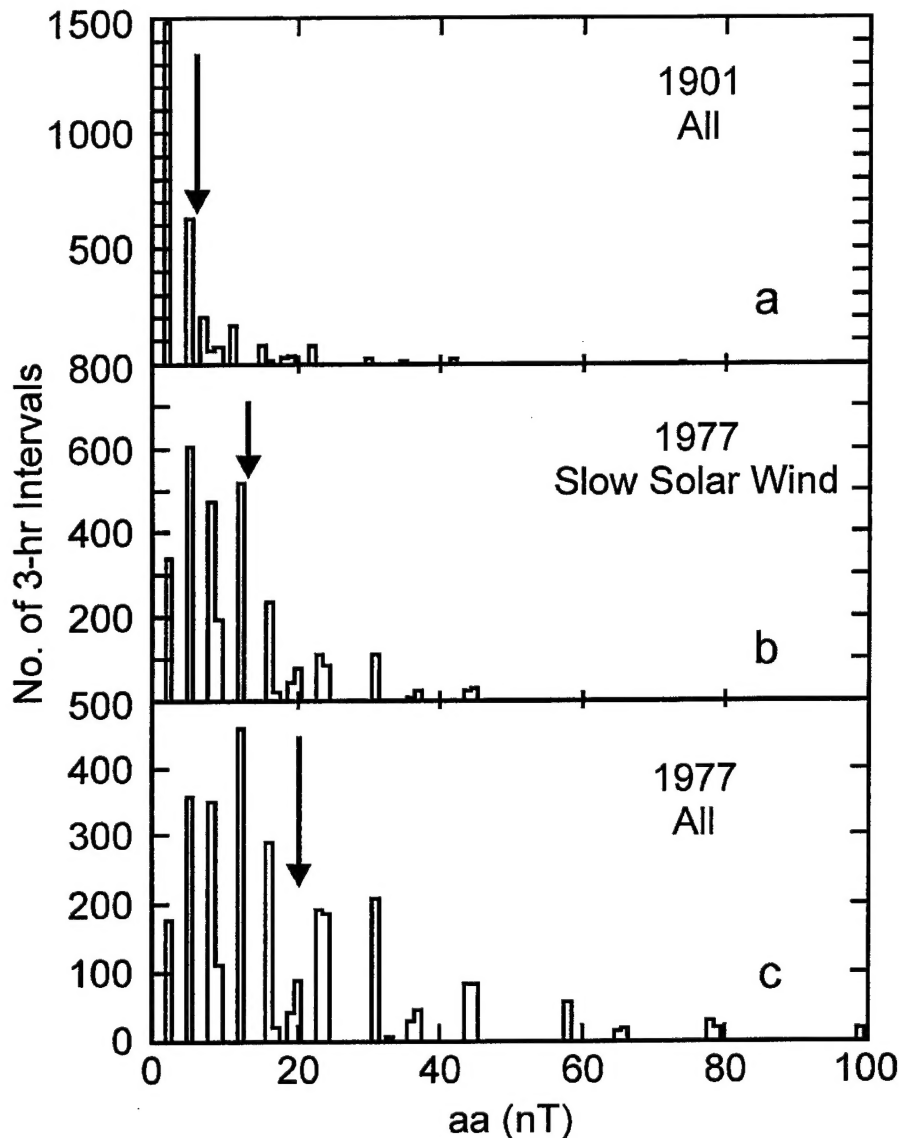


Figure 3. Distributions of the 3-hour aa index for (a) all solar wind regions in 1901, and (b) for slow solar wind and (c) all solar wind in 1977. Arrows indicate average values, and the 1977 slow solar wind distribution is normalized to 1 year. Note that activity levels in 1901 were even less than those observed in slow solar wind in 1977.

rate at the peak of cycle 14 (1902–1913). The smoothed peak (average) sunspot number in cycle 14 was 64.2 (32.3), compared with 164.5 (81.2) for cycle 21. From the relationship of *Webb and Howard* [1994], we then deduce a peak CME rate of ~ 1.1 CME/day for cycle 14. This is 50–60% lower than the peak ~ 2.5 CME/day rate for cycle 21. Based on the analysis of *Richardson et al.* [2000] [see also *Richardson et al.*, 2002], we determined that during the peak years of cycle 21, the Earth spent about one third of the time in each of the three principal components of the solar wind: CME-related flows (including transients, shocks, and post-shock flows), high-speed streams, and slow solar wind. Our CME-rate estimate for cycle 14 suggests that Earth would have been embedded in CME-related flows for only $\sim 15\%$ of the time during the

maximum of that cycle (assuming that these flows had similar characteristic sizes in both cycles).

[12] *Richardson et al.* [2000] also determined the mean values of aa associated with these different types of solar wind flows during cycle 21. Taking average values (for the maximum of cycle 21; 1978–1982) of $aa \sim 35$ nT for CME-related flows, ~ 25 nT for high-speed streams, and ~ 15 nT for slow solar wind, a one-third mix of each solar wind type implies $aa \sim 25$ nT. If we reduce the fraction of CME-related flows to $\sim 15\%$ (appropriate for cycle 14) and assume that the remainder of the solar wind is equally divided between slow solar wind and high-speed streams, then we get an average aa of ~ 22 nT. Taking a more extreme case where the CMEs are embedded in slow solar wind flow yields $aa \sim 18$ nT. However, Figure 2b indicates

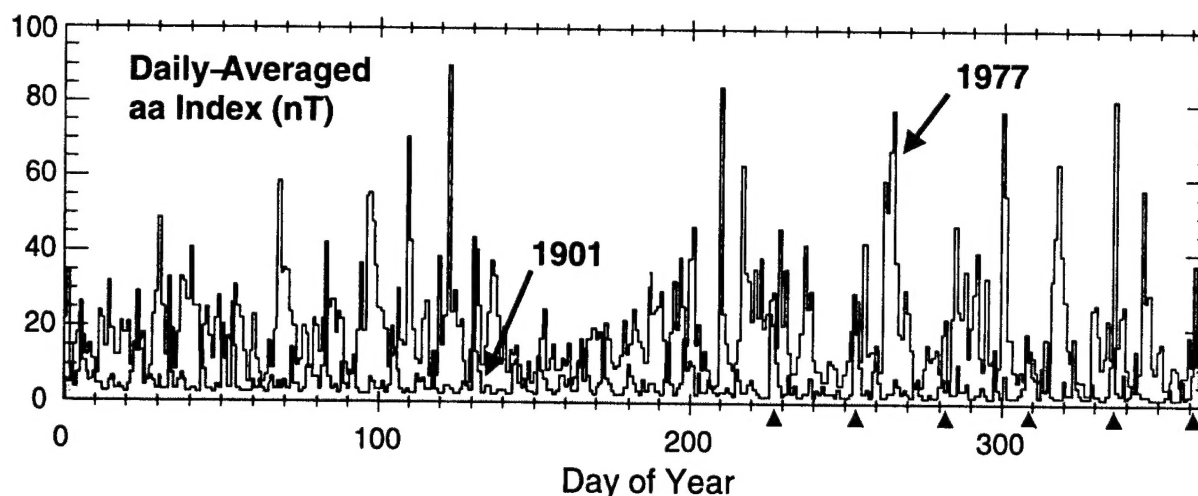


Figure 4. Comparison of the daily-averaged *aa* index in 1901 (shaded) and 1977, showing the persistently lower values attained in 1901. Some intervals of relatively enhanced activity in 1901, most clearly after day 200 and indicated by arrowheads, show evidence of recurrence at the solar rotation period, suggesting that corotating streams were present.

that *aa* early in the twentieth century was lower than each of these estimates (for example, the average *aa* during the maximum of cycle 14 (1904 – 1909) was ~ 15 nT), showing that the increase in *aa* since this time did not arise solely from the inferred change in the CME rate. Only by completely excluding CMEs and assuming that only slow solar wind was present in the solar wind 100 years ago can we obtain a value of *aa* (~ 15 nT) matching that for the peak of cycle 14. However, we know that even great transient storms occurred early in the twentieth century (e.g., the September 1909 storm associated with low-latitude aurorae [Silverman, 1995]), so a CME-associated component of the solar wind was certainly not completely absent at this time. In addition, as we will show below, corotating streams were also present during this period. Thus, we conclude that the cause of the increase in *aa* from $\sim 1900 - 1950$ cannot be simply due to a change in solar wind structure.

3.2. A Comparison of the *aa* Minimum Years of 1901 and 1977

[13] To examine the structure of the “background” solar wind at the beginning of the twentieth century, it is instructive to compare *aa* during a minimum year at the beginning of the twentieth century (1901) and for a recent cycle (1977). Distributions of 3-hour values of *aa* for these years are shown in Figures 3a and 3c, respectively, while Figure 3b illustrates the similar distribution for periods of slow solar wind in 1977 (normalized to 1 year). We note that the average *aa* for all solar wind in 1901 (~ 6 nT; shown by the arrow) was lower than that for slow solar wind in 1977 (~ 13 nT), which in turn was below the 1977 value for all solar wind (~ 20 nT). Thus, the low levels of geomagnetic activity at the beginning of the twentieth century did not simply arise because the Earth was immersed at that time in solar wind with characteristics similar to those of slow solar wind detected during the space era. Eliminating both CMEs and high speed streams from

the 1977 solar wind still leaves a solar wind that is twice as geoeffective as the average solar wind for 1901. Evidence that slow solar wind during 1977 is more geoeffective than that in 1901 can also be inferred from Figure 2 [after Vennerstroem, 2000] where it is shown that the increase in average *aa* during the first half of the twentieth century (Figure 2b) was apparent on the quietest days (Figure 2c) presumably dominated by the slow solar wind. The activity increase was also seen on the most active days (Figure 2a) suggesting that CME-related structures likewise became more geoeffective during this period.

[14] Figure 4 compares time series of daily-averaged *aa* values in 1901 and 1977. Again, it is evident that activity levels on the quietest days in 1977 were higher than those generally found in 1901. Note that there were relatively brief intervals of enhanced activity in 1901. Some of these appear to recur at the ~ 27 day solar rotation period (examples are indicated by arrowheads), suggesting that they are associated with corotating high-speed streams [e.g., Crooker and Cliver, 1994]. The presence of recurrent structures is confirmed by the Lomb periodogram [Lomb, 1976] for the 3-hr *aa* index in 1901 shown in Figure 5. Prominent peaks are centered on periods of $\sim 26 - 28$ days. These results show that the low values of *aa* at the beginning of the twentieth century do not correspond to a structureless “ground state” of the solar wind. Figure 4 also shows that the recurrent activity increases in 1901 were less intense than those in 1977, indicating that the relative geoeffectiveness of corotating high-speed streams was also less in 1901 than in 1977. In fact, Clilverd *et al.* [1998] attribute the increase in *aa* during the first half of the twentieth century primarily to an increase in recurrent storm activity.

[15] The reduced geoeffectiveness of slow- and high-speed streams ~ 100 years ago implies either a lower IMF strength at that time, or lower solar wind speeds, or both [Feynman and Crooker, 1978]. Since we observe that, in recent solar cycles, variations of *aa* have been accom-

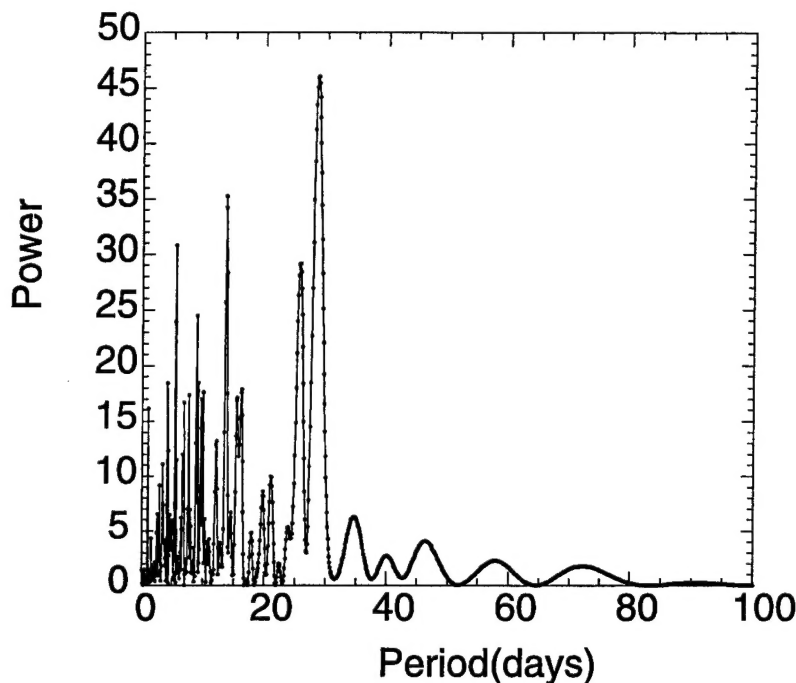


Figure 5. Lomb periodogram for the 3-hr averaged *aa* index in 1901, showing peaks in the power at approximately the whole and half solar rotation period (~ 27 and 13.5 days) indicating the presence of corotating structures.

panied by similar variations in the IMF strength (e.g., Figure 1), it is likely that the general increase in *aa* from $\sim 1900 - 1950$ involved a long-term change in the IMF such as has been proposed by Lockwood *et al.* [1999]. Moreover, since the solar-cycle variations in the IMF strength are manifested in each solar wind component [Richardson *et al.*, 2000, 2002], it seems likely that a long-term increase in the IMF will involve high-speed streams and CMEs as well as slow solar wind. Note that because the long-term increase in *aa* occurred during the first half of the twentieth century, and *aa* has subsequently on average been more constant (Figure 1), a long-term increase in the IMF strength is not inconsistent with the absence of an increase during the second half of the century as inferred in Section 2. The large increase (nearly a doubling) of *aa* during the first half of the twentieth century indicates that changes in the IMF and/or solar wind speed were substantial during this period.

4. Summary and Discussion

[16] The Lockwood *et al.* [1999] report that the Sun's open magnetic field has doubled during the past century has generated a great deal of interest, leading to this special section of the Journal of Geophysical Research. Arge *et al.* [2002] point out that the related finding by Stamper *et al.* [1999] of a $\sim 40\%$ increase in the radial component of the IMF during the space age is not reflected in an increase in the open flux at the Sun deduced from measurements at three separate solar observatories since 1974. We show above that the inferred $\sim 40\%$ increase arises largely because of the difference in IMF strength between cycles

20 (1964–1976) and 21 (1976–1986) (Figure 1), and should therefore not be regarded as a long-term or secular trend. For the post-1974 period considered by Arge *et al.*, we find no evidence for an increase in the average radial component of the IMF. Indeed, there is a slight downward trend when one includes data for current cycle 23. Similarly, the $\sim 40\%$ increase in the *aa* index during 1964–1996 reported by Stamper *et al.* [1999] is largely the result of weak geomagnetic activity during cycle 20 and is not evidence for a long-term trend.

[17] A consideration of galactic cosmic ray data, an indirect indicator of IMF strength, reinforces the evidence that there is no long-term increase in IMF since the early 1950s (Figure 1). We note that Mursula *et al.* [2001] inferred only a weak downward gradient in the average Climax neutron monitor intensity since 1951. They concluded that the trend found by Stamper *et al.* [1999] and also by Lockwood [2001] and Lockwood and Foster [2000] combined with these authors' assumption of a linear relationship between the solar open magnetic field and the cosmic ray intensity, implies unphysically high cosmic ray intensities early in the twentieth century. Stozhkov *et al.* [2000] have also concluded that there is a weak long-term decline (few hundredths of a percent/year) in the cosmic ray intensity at a wide range of rigidities based on a more comprehensive study than we have attempted here. They suggest that this decrease could be explained by a supernova explosion at a distance of 30–150 pc about $10^4 - 5 \times 10^5$ years ago, rather than by changes at the Sun, interplanetary space, or the Earth's magnetosphere, though they note that it is difficult to rule out such effects completely [cf. Ahluwalia and Lopate, 2001].

[18] As the second topic of this paper, we investigated the origin of the upward trend in aa during the first half of the twentieth century. While the case for a clear trend in solar, solar wind, and geomagnetic conditions during the space age is problematic (Figure 1), the marked increase in aa between 1900 and ~ 1950 (substantiated by corresponding increases in several other geomagnetic indices [Cliver and Ling, 2002] and its reflection in the sunspot number envelope [e.g., Cliver et al., 1998]) provides strong evidence for a significant secular change in the Sun's open magnetic flux as suggested by Lockwood et al. [1999] and/or solar wind speed (see Feynman and Crooker [1978]). In this study, we entertained the idea that the low values of aa for sunspot cycles at the turn of the twentieth century might have resulted from a reduction in the rate of CMEs and a circumstance where Earth experienced only slow solar wind, the least geoeffective of the three basic flow types. We inferred that CMEs were present 100 years ago, but would have occurred at about half the present rate. This change in the CME rate, and an accompanying change in the frequency and extent of high-speed streams [Clilverd et al., 1998] however are insufficient to account for the change in aa .

[19] We presented evidence that the slow solar wind early in the last century was significantly less geoeffective than that of today [see also Vennerstroem, 2000]. We conclude that the rise in aa during the first half of the twentieth century did not result solely from a change in solar wind structure (e.g., an increased rate of CMEs) but also involved a general increase in the geoeffectiveness of the solar wind (related to increases in the IMF and/or solar wind speed) that is evident in the slow solar wind and most likely involved CMEs and corotating high-speed streams as well.

[20] **Acknowledgments.** H.V.C. was supported at GSFC by a contract with USRA. I.G.R. was supported by NASA grant NCC 5-180. We acknowledge the use of OMNI near-Earth solar wind data supplied by the National Space Science Data Center. The aa data were obtained from the NOAA National Geophysical Data Center. The Climax data were provided by the University of Chicago neutron monitor database (<http://ulysses.uchicago.edu/NeutronMonitor/>) supported by National Science Foundation Grant ATM-9912341.

[21] Janet G. Luhmann thanks Jozsef Kota and another referee for their assistance in evaluating this paper.

References

- Ahluwalia, H. S., and C. Lopate, Long term residual modulation of lower energy galactic cosmic rays, *Conf. Pap. Int. Cosmic Ray Conf. 27th*, 9, 3834, 2001.
- Arge, C. N., E. Hildner, V. J. Pizzo, and J. W. Harvey, Two solar cycles of nonincreasing magnetic flux, *J. Geophys. Res.*, 107, 10.1029/2001JA000503, in press, 2002.
- Belov, A., Large scale modulation: View from Earth, *Space Sci. Rev.*, 93, 79, 2000.
- Cane, H. V., G. Wibberenz, and I. G. Richardson, Solar magnetic field variations and cosmic ray modulation, in *Solar Wind Nine*, edited by S. R. Habbal et al., *AIP Conf. Proc.*, 471, 99, 1999a.
- Cane, H. V., G. Wibberenz, I. G. Richardson, and T. T. von Rosenvinge, Cosmic ray modulation and the solar magnetic field, *Geophys. Res. Lett.*, 26, 565, 1999b.
- Clilverd, M. A., T. D. G. Clark, E. Clarke, and H. Rishbeth, Increasing magnetic storm activity from 1868 to 1995, *J. Atmos. Sol. Terr. Phys.*, 60, 1047, 1998.
- Cliver, E. W., and A. G. Ling, Secular change in geomagnetic indices and solar open magnetic flux during the first half of the twentieth century, *J. Geophys. Res.*, 107, 10.1029/2001JA000505, in press, 2002.
- Cliver, E. W., O. C. St. Cyr, R. A. Howard, and P. S. McIntosh, Rotation-averaged rates of coronal mass ejections and dynamics of polar crown filaments, in *Solar Coronal Structures: IAU Colloquium 144*, edited by V. Rusin, P. Heinzel, and J.-C. Vial, p. 83, VEDA, Bratislava, 1994.
- Cliver, E. W., V. Boriakoff, and K. H. Bounar, Geomagnetic activity and the solar wind during the Maunder Minimum, *Geophys. Res. Lett.*, 25, 897, 1998.
- Crooker, N. U., and E. W. Cliver, Postmodern view of M-regions, *J. Geophys. Res.*, 99, 23,383, 1994.
- Crooker, N. U., and K. I. Gringauz, On the low correlations between long-term averages of solar wind speed and geomagnetic activity after 1976, *J. Geophys. Res.*, 98, 59, 1993.
- Crooker, N. U., J. Feynman, and J. T. Gosling, On the high correlation between long-term averages of the solar wind speed and geomagnetic activity, *J. Geophys. Res.*, 82, 1933, 1977.
- Feynman, J., and N. U. Crooker, The solar wind at the turn of the century, *Nature*, 275, 626, 1978.
- Gosling, J. T., D. J. McComas, J. L. Phillips, and S. J. Bame, Geomagnetic activity associated with Earth passage of interplanetary shock disturbances and coronal mass ejections, *J. Geophys. Res.*, 96, 7831, 1991.
- Jokipii, J. R., and B. T. Thomas, Effects of drift on the transport of cosmic rays: Modulation by a wavy interplanetary current sheet, *Astrophys. J.*, 243, 1115, 1981.
- Kota, J., and J. R. Jokipii, Effects of drift on the transport of cosmic rays: A three-dimensional model including diffusion, *Astrophys. J.*, 265, 573, 1983.
- Lockwood, M., Long-term variations in the magnetic field of the Sun and the heliosphere: The origin, effects, and implications, *J. Geophys. Res.*, 106, 16,021, 2001.
- Lockwood, M., and S. Foster, Long-term variations in the magnetic field of the Sun and possible implications for terrestrial climate, in *The Solar Cycle and Terrestrial Climate*, edited by A. Wilson, *Eur. Space Agency Spec. Publ.*, ESA SP-463, 85, 2000.
- Lockwood, M., R. Stamper, and M. N. Wild, A doubling of the sun's coronal magnetic field during the last 100 years, *Nature*, 399, 437, 1999.
- Lomb, N. R., Least-squares frequency analysis of unequally spaced data sets, *Astrophys. Space Sci.*, 39, 447, 1976.
- Mayaud, P. N., The aa indices: A 100-year series characterising the geomagnetic activity, *J. Geophys. Res.*, 72, 6870, 1972.
- Mursula, K., I. G. Usokin, and G. A. Kovaltsov, Long-term cosmic ray intensity vs. solar proxies: A simple linear relation does not work, *Conf. Pap. Int. Cosmic Ray Conf. 27th*, 9, 3839, 2001.
- Popielawska, B., and J. A. Simpson, Cosmic ray observations in the changing geomagnetic field, *Conf. Pap. Int. Cosmic Ray Conf. 22nd*, 3, 660, 1991.
- Richardson, I. G., E. W. Cliver, and H. V. Cane, Sources of geomagnetic activity over the solar cycle: Relative importance of CMEs, high-speed streams, and slow solar wind, *J. Geophys. Res.*, 105, 18,203, 2000.
- Richardson, I. G., E. W. Cliver, and H. V. Cane, Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000, *Geophys. Res. Lett.*, 28, 2569, 2001.
- Richardson, I. G., H. V. Cane, and E. W. Cliver, Sources of geomagnetic activity during nearly three solar cycles (1972–2000), *J. Geophys. Res.*, 107, 10.1029/2001JA000504, in press, 2002.
- Russell, C. T., On the possibility of deducing interplanetary and solar parameters from geomagnetic records, *Sol. Phys.*, 42, 259, 1975.
- Shea, M. A., and D. F. Smart, Fifty years of cosmic radiation data, *Space Sci. Rev.*, 93, 229, 2000.
- Shea, M. A., and D. F. Smart, Vertical cutoff rigidities for cosmic ray stations since 1955, *Conf. Pap. Int. Cosmic Ray Conf. 27th*, 10, 4063, 2001.
- Silverman, S. M., Low latitude auroras: the storm of 25 September 1909, *J. Atmos. Sol. Terr. Phys.*, 57, 673, 1995.
- Slavin, J. A., and E. J. Smith, Solar cycle variations in the interplanetary magnetic field, in *Solar Wind Five*, edited by M. Neugebauer, *NASA Conf. Publ.*, 2280, 323, 1983.
- Stamper, R., M. Lockwood, M. N. Wild, and T. D. G. Clark, Solar causes of the long-term increase in geomagnetic activity, *J. Geophys. Res.*, 104, 28,325, 1999.
- Stozhkov, Y. I., P. E. Pokrevsky, and V. P. Okhlopov, Long-term negative trend in cosmic ray flux, *J. Geophys. Res.*, 105, 9, 2000.
- Vennerstroem, S., Long-term rise in geomagnetic activity: A close connection between quiet days and storms, *Geophys. Res. Lett.*, 27, 69, 2000.
- Webb, D. F., and R. A. Howard, The solar cycle variations of the occurrence rate of coronal mass ejections and the solar wind mass flux, *J. Geophys. Res.*, 99, 4201, 1994.
- H. V. Cane and I. G. Richardson, Code 661, Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (hilarly.cane@utas.edu.au; richardson@lhea.gsfc.nasa.gov)
- E. W. Cliver, Air Force Research Laboratory, Hanscom AFB, MA 01731, USA. (cliver@plh.af.mil)